Pulsed Electric Fields 008093

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The concept of pulsed electric fields (PEF) was first proposed in 1967 to change the behavior or microorganisms. The electric field phenomenon was identified as membrane rupture theory in the 1980s. Increasing the membrane permeability led to the application of PEF assisted extraction of cellular content and transfer of genetic material across cell membrane. The lethal effects of PEF to microorganisms were studied in 1990s when laboratory and pilot plant equipment were developed to evaluate the effect of PEF as a nonthermal food process to provide consumers with microbiologically-safe and fresh-like quality foods. Application of high voltage electric field at a certain level for a very short time by PEF not only inactivates pathogenic and spoilage microorganisms, but also results in the retention of flavor, aroma, nutrients, and color of foods. The first commercial PEF pasteurization of apple cider products took place in 2005 in the United States. This paper provides current information about PEF food processing and identifies a list of research needs to further develop PEF technology for food processing and preservation.

Key Words: Pulsed electric fields, nonthermal, pasteurization, quality, research needs

INTRODUCTION

Pulsed electric fields (PEF) utilize intensive electric pulses to inactivate microorganisms in a fluid, and are typically applied to the fluid in a continuous flow. The field intensity is in the range 15–50 kV/cm, but this field is only required for microseconds. PEF remains a nonthermal process because the energy required for microbial inactivation is small compared to thermal processes, and it only raises the fluid temperature by a few degrees. The applied intensive electric field creates a trans-membrane potential difference high enough to cause the lipid membrane to break down. Permanent damage to the membrane is achieved when the electric field at the membrane goes beyond critical field strength, in the range 5–15 kV/cm. As a result of this permanent membrane damage, microorganisms are inactivated. Some applications of PEF technology are in biotechnology and genetic engineering for electroporation in cell hybridization (Chang et al., 1992), PEF assisted extraction of sugar and other cellular contents, and PEF assisted waste treatment to reduce effluent volume (Jeyamkondan, 1999).

A typical PEF processing system consists of a pulse modulator and a set of PEF treatment chambers. The pulse modulator has evolved from using spark gaps as switching devices to current semiconductor switching devices. The new pulse modulators using semiconductor switches are called solid-state pulse modulators. These modulators can turn pulses on and off to generate a nearly square pulse waveform. The spark-gap switches such as the ignitron, thyratron, and air-gap switches can be triggered to turn on, but not off, thus generating exponential decay wave forms (usually). The PEF treatment chambers can accept typical geometries of parallel plates, co-field flow, and coaxial cylinders. Food flows through the treatment chamber to receive the pulsed field treatment.

PEF processing has been studied by a number of researchers across a wide range of liquid foods. Apple and orange juices are among the foods most often treated in PEF studies. The sensory attributes of juices are reported to be well preserved, and the shelf life is extended. Yogurt drinks, apple sauce, and salad dressing have also been shown to retain a fresh-like quality with extended shelf life after processing. Other PEF-processed foods include milk, tomato juice (Min et al., 2003), carrot juice, pea soup (Vega-Mercado et al., 1996), liquid whole egg (Martin-Belloso et al., 1997), and liquid egg products. Some studies have reported that color was better maintained in some juices and liquid eggs treated by PEF than in those treated with heat or other process. Also, cakes made with

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PEF-treated eggs showed better strength than those made with non-processed eggs. PEF processing of highly viscous foods, foods with particulates, and solid foods needs further investigation.

PEF is also effective in the inactivation of yeasts, molds, and vegetative bacteria in liquid medium. In general, larger size cells and cells with weaker membrane structure are more sensitive to PEF treatment (Grahl and Märkl, 1996). A number of other factors during PEF processing can affect specific microbial inactivation as well. Some of these critical factors include the field strength, treatment time, treatment temperature, pulse shape, type of microorganism, growth stage of microorganism, and characteristics of the treatment substrate. A wealth of literature exists reporting the inactivation of microorganisms by PEF. Due to the variability in process parameters used, direct comparisons on the kinetics of microbial reduction achieved with different PEF systems are rather difficult.

STATE-OF-ART OF THE TECHNOLOGY

The concept of PEF was first proposed in the 1960s (Sale and Hamilton, 1967a,b). Scientific research followed in the 1980s, showing that microbial inactivation by PEF was real and predictable. PEF is reported to achieve more than 5 log reductions for *Eschericia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* in apple cider (Lu et al., 2001), orange juice (Liang et al., 2002), and dairy milk (Reina et al., 1998). Technological development in the 1990s moved this process from the laboratory to readiness for industrial production evaluations. As has been true for other nonthermal processes, commercial application of the PEF process started in a niche market with fresh juices. The first commercial products in the US, consisting of all natural PEF-pasteurized fruit juices and mixes, were successfully introduced in the fall of 2005 in the Pacific Northwest.

With fluorescence imaging, membrane damage was identified as the primary mechanism of PEF inactivation. This is believed to be due to membrane rupture (electroporation), resulting in irreversible breakdown of the cell membrane at high intensity electric fields. This disruption in the cell membrane can cause the cell contents to leak out, and thus the microbial metabolism is affected (Sale and Hamilton, 1968).

A major breakthrough in the feasibility of PEF processing was demonstrated under a US Army funded consortium, which utilized solid state pulse modulators in place of the earlier spark gaps or vacuum tubes to provide the high voltage pulses needed for PEF. This solid state technology was originally developed for radar transmitters and large particle accelerators. It provides significant improvements in pulse control (such as controllable pulse width and pulse frequency). Solid state pulse modulators, for the first time, made it possible to vary and assess PEF parameters very rapidly, simplifying research of PEF and allowing optimization of these parameters for specific products. This technology provided the scalability to large PEF systems needed for commercial applications, as demonstrated in the first commercial scale PEF system delivered to Ohio State University by Diversified Technologies, Inc., in 2000. Solid state PEF systems have also proven significantly more reliable, and easier to operate than earlier systems, allowing use by operators with similar levels of training and the same expertise required for other commercial food processing systems.

Optimization of PEF process equipment for commercial use is ongoing, but much remains to be accomplished. Most of the studies on fluid foods have involved a continuous system, but a few studies have tested static chambers. A range of electrode designs for the treatment chambers exist, but parallel plates, co-field flow, and coaxial cylinders are most commonly used, while other electrode configurations, such as rod–rod or rod–plate, have been identified but not well characterized (Qin et al., 1995). No definitive conclusions can yet be drawn concerning the impact of these system variations on microbial inactivation, due to the variability in parameters used across these studies. Also, different types of pulse waveforms have been used, but square wave pulses are considered more energy efficient in inactivating microorganisms than exponentially decaying or oscillatory decaying pulses, because they provide maximum exposure time beyond the critical electric field strength.

PEF technology faces some limitations. The initial cost of installing the equipment is higher than for thermal pasteurization, although energy savings with PEF may compensate for this up-front cost over time. Assessments of this cost tradeoff are complicated because, unlike thermal processing, the energy required for PEF processing varies across different foods, since the food is actually part of an electrical circuit. As the product conductivity rises, more energy will be required for treatment, and both the food type and its processing prior to treatment can affect conductivity. Fruit juices have lower electrical conductivity than vegetable juices, for example, and salted foods have higher conductivity than unsalted foods.

Commercial scale processing systems that handle 2000–50,000 L/h are only now becoming commercially available, and the transition of this equipment from scientific use to commercial processing will require optimizations of equipment packaging and controls/automation. The efficacy of processing low acid foods, and remaining research issues concerning treatment of particulate foods, limit their current scope of applicability. The presence of air bubbles in a product may cause problems in the system's operation, and some products may need to be de-aerated prior to PEF processing (Barsotti et al., 1999). Finally, some researchers have tested the feasibility of using PEF on dry spice powders and flour, but they experienced problems with arcing and corona discharge due to the nonfluid nature of the media (Keith, 1997).

RESEARCH NEEDS

Although many researchers have investigated PEF for several years and initial commercial production has been achieved in food processing, several areas require further research, as elaborated in following:

1. Fundamental research needs
   - Characterizing the interactions of electric fields with various food matrices at the molecular level.
   - Studying the chemistry and electrochemistry at/near the electrode area during PEF treatment.
   - Identifying the mechanisms of inactivation of bacterial cells, especially in a continuous system, at cellular and molecular levels.
   - Screening of microorganisms (pathogens as well as surrogates) most resistant to PEF.
   - Measuring the time dependent response of the cell membrane to PEF treatment.
   - Observing interactions of the microbial cells with electric fields microscopically.
   - Standardizing and quantifying PEF processing variables and their contribution to the mechanism of inactivation.
   - Studying the effects of PEF on enzyme activities.
   - Comparing PEF and heat resistance of enzymes.
   - Identifying the mechanisms of enzyme inactivation by PEF at the molecular-structure level.
   - Providing science-based information for public awareness and education.
2. Process dosage uniformity and monitoring
   - Controlling/monitoring residence time (i.e., length of time food remains in chamber).
   - Controlling residence time distribution by matching the flow profile and fluid conductivity with the electric field distribution.
   - Designing multiple PEF chambers to ensure minimum treatment time.
   - Developing direct and indirect monitors for PEF dosage delivered to foods.
   - Validating methods to accurately measure the treatment delivery.
   - Developing and validating inactivation kinetic models.
   - Selecting and optimizing critical process parameters for enhanced microbial inactivation across a range of foods and microorganisms.
3. Pulsed power equipment
   - Identifying the effects of different pulse waveforms.
   - Quantifying the need for and/or benefits of bipolar pulses.
   - Designing a system to detect, avoid, and tolerate occasional arcing during PEF processing.
   - Improving pulsed power system reliability, controllability, and user friendliness.
   - Increasing the life of electrodes in continuous operations.
   - Designing pulsed power systems for processing of large flow rate for bulk foods.
   - Reducing equipment and operations costs.
4. Food matrix
   - Identifying the effects of food composition.
   - Designing PEF systems to process particulate and solid foods.
5. Synergy and combination
   - Understanding the effect of holding temperature and holding time after PEF process.
   - Identifying the benefits when PEF is combined with other thermal and nonthermal technologies.
   - Identifying antagonistic effects of other processing and environmental variables.
   - Testing the use of supplementary chemicals or natural antimicrobials in combination with PEF to reduce process intensity.
   - Investigating inactivation of spores by PEF and the mechanisms involved.
   - Identifying combination processes for spore inactivation.

CRITERIA TO ESTABLISH PRIORITIES FOR RESEARCH NEEDS

Prioritizing the research needs for PEF should depend on three major criteria. First, it is crucial that PEF technology should assure public safety and high product quality compared to existing food processing technologies. Therefore, the first criterion for setting priorities must consider the question, 'what is the impact of the technology on public life?'

The second criterion for setting priorities should be governmental regulations for approval of the technology. Since regulatory approval is based on sound science, fundamental studies are needed to enable the technology to pass regulatory barriers.

Finally, priorities must be based on consideration of how the economic viability of PEF can be improved. Even the most effective PEF process will not be adopted and made available for consumer products if it cannot compete economically with alternatives.

Research Areas to Invest Public Funds

Several fundamental and applied issues that are unclear regarding PEF technology have been listed above as needing further investigation. Research in those areas would be a wise investment of public research dollars. Funding for such research must cover:

- Fundamental research
- Applied research
- Validation of feasibility studies

Ideas for Partnerships to Address Research Needs

Ideas for partnerships that can be formed to address the PEF issues in need of further research follow:

- Consortia formed can consist of federal agencies, including the National Center for Food Safety and Technology, USDA ARS Eastern Regional Research Center, and US Army Natick Soldier Center, along with universities, equipment manufacturers, and the food industry. These consortia can work collaboratively to solve problems related to food safety and intervention technologies, gaining an understanding of issues related to emerging nonthermal technologies.
- Small Business Innovative Research (SBIR) grants and Small Business Technology Transfer (STTR) grants would allow for partnerships between industry and academia.
- A PEF Forum (national/international) can be formed wherein scientists working on the technology and others interested in the technology can share ideas periodically, publish newsletters, meet annually, review progress, and discuss future/further needs for this technology. This forum would promote the technology towards regulatory approval and commercialization.
- Educational grants can help with the development of short courses, symposia, workshops, or conferences related to the technology.

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